

## **Method for Detecting Chemical Interactions Between Naturally Occurring Bio-Polymers Which Are Non-Identical Binding Partners**

### **Field of the Invention**

The present inventors claim priority to U.S. Provisional No. 60/049,707 filed June 16, 1997, which is hereby incorporated by reference for all it discloses and for all purposes.

The present invention relates to the field of micromechanical devices as sensors for detecting physical or chemical changes caused by chemical interactions between naturally occurring bio-polymers which are non-identical binding partners, such as can occur with polyamino acids, polynucleotides, and the like. The method of the present invention is useful whether the reactions occur through electrostatic forces or through other forces. In particular, the present invention provides a method for detecting chemical interactions between naturally occurring bio-polymers which are non-identical binding partners where one binding partner or probe molecule is placed on a cantilever for possible reaction with a sample analyte molecule (i.e., a non-identical binding partner). The physical or chemical change may be induced stress, heat, or mass, for example. The present invention is particularly useful in determining DNA hybridization but may be used in detecting interactions between any analyte molecules, whether monomeric or polymeric. Examples of polymer arrays which can be used with the method of the present invention include nucleic acid arrays, protein or polypeptide arrays, carbohydrate arrays, and the like.

### **Background of the Invention**

As known in the art, various techniques have been used to determine whether a chemical interaction has occurred between two materials, such as between a probe carrying a binding partner and a sample. In the specific example of determining whether DNA hybridization has occurred, various techniques have been used to extract information from a sample. For example, detection schemes have been used that are responsive to fluorescence in order to reveal specific interactions or

hybridizations. U.S. Patent No. 5,578,832, "Method and Apparatus for Imaging a Sample on a Device," issued to Trulson et al. ("the '832 patent") and U.S. Patent No. 5,631,734, "Method and Apparatus for Detection of Fluorescently Labeled Materials," issued to Stern et al. ("the '734 patent") provide methods and systems for detecting a labeled marker on a sample located on a support through the use of an excitation radiation source and radiation optics. The '832 patent and the '734 patent are hereby incorporated by reference for all they disclose and for all purposes. As described in the '832 and '734 patents, these techniques employ the use of a label, for example, the DNA probe is labeled with a fluorescent molecule, such as fluorophore or biotin. Once the DNA probe is labeled according to prior methods, an optical system can be used to determine whether hybridization has occurred by measuring fluorescence activated between the labeled sample and the probe material.

The present invention provides a method for determining whether a chemical interaction has occurred between naturally occurring bio-polymers which are non-identical binding partners through detecting a physical or chemical change on a micromechanical device called a cantilever. A cantilever, by way of analogy, can be thought of as a diving board which has been reduced to a very small size. More specifically, a cantilever is a physical device that is attached to another object at one end and remains free to move on the other end. Deflection or up and down movement of the free end of the cantilever can then be detected. The method of the present invention can be used with any chemical analyte to generate a physical or chemical change, whether through affinity binding, which may include hydrogen bonding, electrostatic attractions, hydrophobic effects, dipole interactions, or through other forces.

The use of micromechanical sensors is advantageous in the method of the present invention for several reasons. Various signals such as force, heat, stress, magnetism, charge, radiation and chemical reactions can be readily transduced into a micromechanical deflection by an appropriately coated structure, such as a cantilever. In addition, silicon-based micromechanical devices can easily be integrated into microelectronic processing systems such as CMOS (Complementary Metal-Oxide-Semiconductor), as known to one of skill in the art. As a result, it is possible to produce seamless sensors at low cost and to integrate them directly into computers. Moreover, micromechanical sensors are very small, typically approximately 400  $\mu\text{m}$  in length, approximately 40  $\mu\text{m}$  wide and approximately 1

μm thick. As a result, it is possible to obtain a short response time, generally measured in microseconds, as well as sensitivity superior to standard techniques. Finally, it is possible to construct arrays of micromechanical devices, thereby permitting complex analysis of a variety of signals as well as the use of a variety of sensing materials.

By way of background, it is known that stress induced by self-assembled monolayers can be detected by observing the deflection of a micromachined cantilever similar to those used in the commercial Atomic Force Microscope ("AFM"), as described by Berger et al., in "Surface Stress in the Self-Assembly of Alkanethiols on Gold," *Science*, June 27, 1997, Vol. 176, p. 2021 ("Berger I"), which is hereby incorporated by reference for all it teaches. The Berger et al. paper studied the surface stress changes during self-assembly of selected molecules, including alkanethiol molecules self-assembled on gold. The researchers found that the stress increases linearly with the length of the alkyl chain of the molecule. In addition, the researchers detected a change in the state of stress with the formation of salt bridges formed when mercaptohexadecanoic acid was deposited on a functionalized surface coated with the self-assembled thiols. This change in cantilever stress was used to detect the formation of the salt bridges when the analyte molecules were introduced.

Other pertinent work involving micromechanical sensors is reflected in a paper by Berger et al. entitled "Nanometers, Picowatts, Femtojoules: Thermal Analysis and Optical Spectroscopy Using Micromechanics," *Analytical Methods & Instrumentation*, Special Issue, *μTAS '96* ("Berger II"), also incorporated by reference for all it discloses and for all purposes. In Berger II, examples of low-cost, disposable micromechanical devices are described which perform optical absorption spectra, calorimetric and thermal analysis, electrochemical stressograms, gas phase adsorption and surface reaction monitors.

Other work in the area of micromechanical sensors is reported by Gimzewski et al. in "Observation of a chemical reaction using a micromechanical sensor," *Chemical Physics Letters*, Vol. 217, No. 5,6, January 28, 1994, ("Gimzewski") which is hereby incorporated by reference for all it discloses and for all purposes. Gimzewski discloses a calorimeter for sensing chemical reactions. The device is based on a micromechanical silicon lever coated with a layer of aluminum. A sample is deposited on the lever in a thin layer. Heat fluxes are detected by

measuring the deflection of the cantilever induced by the differential thermal expansion of the lever. Specifically, Gimzewski discloses using this technique to review the catalytic conversion of  $H_2 + O_2$  to obtain  $H_2O$ .

It is further known to operate multiple probes for the atomic force microscope. As described by Minne et al., "Automated parallel high-speed atomic force microscopy," Applied Physics Letters, Volume 78, No. 18, May 4, 1998 ("Minne"), which is herein incorporated by reference for all it discloses and for all purposes, an expandable system is provided to operate multiple probes for the atomic force microscope in parallel at high speeds. The cantilever footprint is only 200  $\mu m$  wide which allows the devices to be placed in a one-dimensional expandable parallel array.

Yet another contribution to the art of micromechanical sensors is described by Manalis et al., "Interdigital cantilevers for atomic force microscopy," Applied Physics Letters, Vol. 69, No. 25, December 16, 1996 ("Manalis I"), which is hereby incorporated by reference for all it discloses and for all purposes. In Manalis I, an AFM sensor is described in which a silicon cantilever is micromachined into the shape of interdigitated fingers that form a diffraction grating. When detecting a force, alternating fingers are displaced while remaining fingers are held fixed. As a result, a phase sensitive diffraction grating is created which allows the cantilever displacement to be determined by measuring the intensity of diffracted modes.

Another paper by Lang et al., "Sequential position readout from arrays of micromechanical cantilever sensors," Applied Physics Letters, Vol. 73, p. 383, 1998 ("Lang") describes using a reference cantilever for canceling environmental noise. Lang is hereby incorporated by reference for all it discloses and for all purposes. In Lang, chemically specific responses are extracted in a noisy environment using a sensor to detect specific chemical interactions and an uncoated cantilever as a reference.

Finally, another paper by Manalis et al., "Two dimensional micromechanical bimorph arrays for detection of thermal radiation," Applied Physics Letters, June 16, 1997, (Manalis II) hereby incorporated by reference for all it discloses and for all purposes, describes fabricating arrays of cantilevers and using them as sensitive detectors of head induced stress. Specifically, the cantilevers described by Manalis II were placed on a grid with 50 microns on centers. The present inventors have

determined that this type of array is a suitable substrate for determining, for example, hybridization.

### Summary of the Invention

Rather than using traditional labeling, such as optical or electrochemical labeling, in order to detect chemical interactions between naturally occurring bio-polymers which are non-identical binding partners, the present inventors have determined a new and useful method for "reading" a substrate to determine whether a particular chemical interaction has occurred. In traditional labeling, sample analyte molecules are modified in some way to permit their detection when they combine with the probe molecules. The method of the present invention is particularly useful in the detection of hybridized sites on a DNA probe array. The method of the present invention allows detection of hybridization without modifying either the analyte or the probe molecules, i.e., it requires no labeling.

According to the method of the present invention, a chemical interaction between naturally occurring bio-polymers which are non-identical binding partners is monitored by detecting a physical or chemical change through deflection of a cantilever. The physical or chemical change can be, for example, induced stress on the cantilever which causes the cantilever to move or deflect. Standard AFM techniques are then used to detect the deflection of the cantilever. The physical or chemical change can also be in the form of a heat reaction, which similarly causes the cantilever to deflect or bend where the cantilever is made of two materials, i.e., is a bimorph. A physical or chemical change might also result in a change in mass on the cantilever. In such an example, the resonant frequency of the cantilever will change due to the mass change. Measuring the resonant frequency of the cantilever under such circumstances will allow the physical or chemical change to be detected.

In a specific embodiment of the present invention, oligonucleotides are deposited onto a cantilever. The stress induced by hybridization is detected with methods commonly used for detecting cantilever deflection in the AFM. As is well known to one skilled in the art, these methods are sensitive to the point where deflections less than 0.01 nm can be easily detected. The substrate used according to the method of the present invention allows exploitation of the cantilever's properties in order to detect the hybridized sites.

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -\frac{q}{\epsilon_0} \quad (1)$$

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## Detailed Description of the Invention

According to the present invention, a physical or chemical change on a cantilever is measured in order to monitor the occurrence of a chemical interaction between naturally occurring bio-polymers which are non-identical binding partners, for example, between biological polymers or other analytes, monomeric or polymeric. Typically, the cantilever as used with the method of the present invention is approximately 100  $\mu\text{m}$  in length, 50  $\mu\text{m}$  in width and approximately 1  $\mu\text{m}$  in thickness. When a chemical interaction occurs on the cantilever, a physical or chemical change occurs causing the cantilever to be deflected, i.e., moved up or down at its free end. Such deflection motion can be detected to a very fine degree, for example, up to a fraction of a diameter of an atom.

Turning to the specific example of using the present method to detect DNA hybridization, as shown in Figure 1, the surface of a cantilever 110 is first prepared in order to be able to attach single strands of DNA. Such surface preparations are

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840.

As shown in Figure 2, the device is then preferably mounted into a liquid cell 130, for example, containing an aqueous buffer 140. A detector 150 is employed in which a laser beam 160 is shown on the cantilever and reflects off of the cantilever. The reflected spot 170 of light is used to determine the relative position of the cantilever. In other words, movement of the cantilever can be determined by directly detecting the movement or angle of the reflected laser beam light. This provides a particular advantage in the present method in that it is always possible to obtain a strong signal from the reflected light.

The response from this first deflection on the detector is used as a reference to determine cantilever deflection, as further described. Next, sample analyte molecules, such as DNA is introduced to the surface of the cantilever containing single stranded DNA. The sample analyte molecules will hybridize with selected strands of DNA on the cantilever, as reflected at numeral 180 in Figure 3. As a result, stress is induced on the cantilever which will cause the cantilever to deflect. More specifically, when hybridization occurs, surface pressure results by the addition of negative charges on the surface of the cantilever because DNA is a polyanion. In other words, hybridization causes more electrostatic charges to build up on the cantilever surface which tend to repel one another. Because the sample analyte molecules are only on one surface of the cantilever, the surface of the cantilever deflects due to this repelling action. This deflection will appear on the deflector as a signal 170' in Figure 3 which can be correlated against the reference signal. It should be noted that the method of the present invention can be used with negatively charged analytes (such as DNA) or positively charged analytes. In addition, the method of the present invention can also be used with uncharged analytes because forces other than electrostatic forces, such as dipole forces, can be employed with the present method.

The detector used with the present invention can be any optical detector capable of tracking reflected laser light as known to one of ordinary skill in the art,

for example, can be a split photodiode, linear array of photodetectors, piezo resistance elements or the like.

In an alternative embodiment, shown in Figure 4, a second cantilever 190 can be used as a reference cantilever. The second cantilever 190 is preferably mounted side by side with cantilever 110. In such an embodiment, a surface of the second cantilever 190 is prepared in the same manner as the first cantilever 110 which will be used for hybridization. However, the second cantilever 190 does not have a binding partner, such as single stranded DNA, attached onto one of its surfaces and is not treated with sample analyte molecules, such as DNA. In this case, one signal (numerals 170 and 170' in Figure 4) from each cantilever is detected by the detector and the difference between the reflected light between the two cantilevers is analyzed. The embodiment shown in Figure 4 cancels any spurious motion of the cantilever caused, for example, by the environment, such as the liquid in the container.

In either embodiment, the signals detected by the detector are then analyzed in order to determine whether hybridization, for example, has occurred. If there is a change in position after the sample analyte molecules, such as DNA, have been introduced on the single cantilever (single cantilever embodiment), or if the cantilever carrying the sample analyte molecules, such as DNA, has changed its position in relation to the reference cantilever (two cantilever embodiment), hybridization has been detected.

In yet another embodiment, several pairs of cantilevers could be used, with one cantilever carrying a specific probe molecules and the other cantilever of the pair carrying a non-specific probe molecule or no probe molecule at all. In the context of DNA hybridization, for example, several pairs of cantilevers could be used each carrying a different sequence of single stranded DNA. Multiple pairs of cantilevers organized in such a fashion are known as an array of cantilevers. In an array, each cantilever pair includes one cantilever for hybridization and one neutral or reference cantilever. The difference between signals of each cantilever pair in the array provides the true hybridization signal for that pair, similar to the system described with respect to Figure 4.

With a cantilever array, it is possible to introduce a complex mixture of molecules into the liquid flow cell encompassing the array and to identify those



molecules in the complex by determining which cantilevers hybridize. The number of cantilever pairs which can be used in an array is unlimited. Such a cantilever array has practical utility in both biomedical and environmental applications. An example of an environmental application would be to use such a detector to identify an unknown contaminant in a sample of air or water which might have been infected by environmental terrorists. The possible applications for the method of the present invention are limitless.

In still another alternative embodiment, an interdigital array of cantilevers, as described above by Manalis I, can be used in the method of the present invention. In an interdigital cantilever array, interleaved fingers are built onto a cantilever in the form of a grid. The cantilever deflects one pair of fingers while the other remains stationary.

The method of the present invention is not limited to the particular embodiments disclosed herein and can be employed to detect any chemical interaction between naturally occurring bio-polymers which are non-identical binding partners with accuracy and at a low cost.